Life Prediction Model for Composite Leaf Springs

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From, PES University, India

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Multi-Disciplinary Projects: CFD, Solid Mechanics, Structures etc.
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OBJECTIVE

Objective

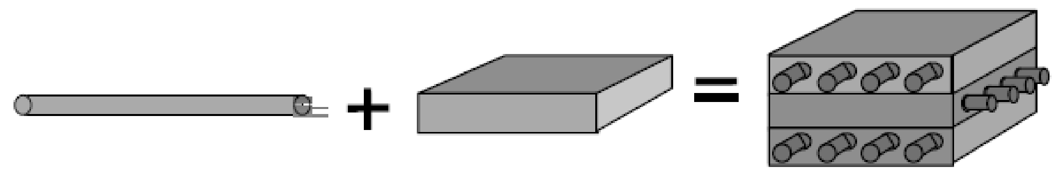
- The objective of this on-going research is to predict the fatigue failure of the composite leaf spring.
- It involves,
  - Understanding the stiffness and mass distribution of an automotive leaf spring using experimental modal analysis.
  - Later the reverse engineered automotive composite leaf spring is considered to predict its fatigue life using finite element method.
  - The finite element model is created using ANSA pre-processor.
  - The Generic Material Degradation method has been introduced to predict the fatigue life of the composite leaf spring.
  - The model will be then be analyzed to fetch stress data corresponding to its life cycle input data.

INTRODUCTION

Composites

Polymer Matrix Composites (PMC) – Different Composite Phases

- Reinforcing Fiber Phase
  - High modulus and strength along fiber direction.
- Matrix Phase
  - Transfers stresses among the fibers.
  - It controls shear, transverse properties and delamination.
- Interface Phase
  - Optimum Stiffness and Strength properties of PMCs with good interfacial stress transfer.
  - A good interfacial stress transfer provides toughness and damage tolerance.



Fiber/Filament Reinforcement
- High strength
- High stiffness
- Low density

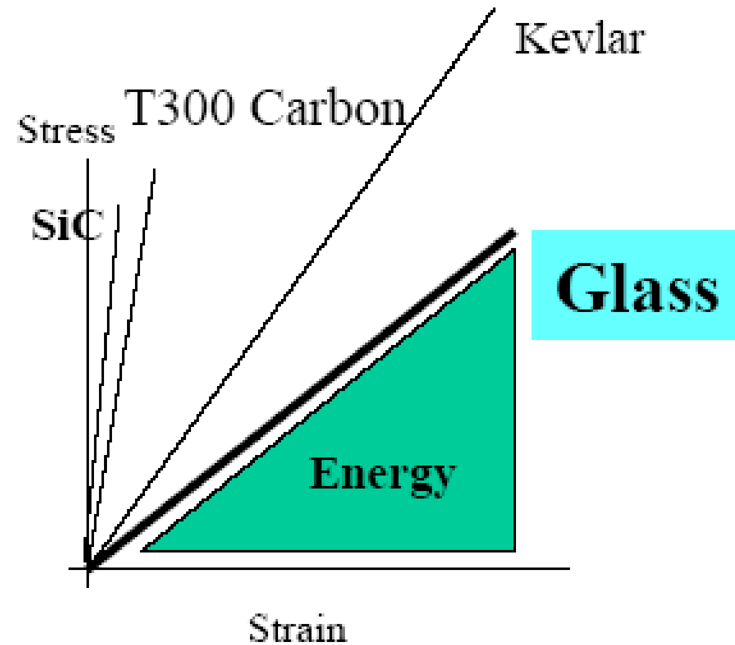
Matrix
- Good shear properties
- Low density

Composite
- High strength
- High stiffness
- Good shear properties
- Low density

Composites

Polymer Matrix Composites (PMC) – Glass Fibers

- **Advantages**
  - Low Cost
  - Relatively easy to handle
  - High Strength
  - Good Impact Resistance/Energy Absorption
- **Disadvantages**
  - Lower Modulus
  - Mechanical Properties Degrade when exposed to Moisture
  - Life under long term sustained load can be limiting

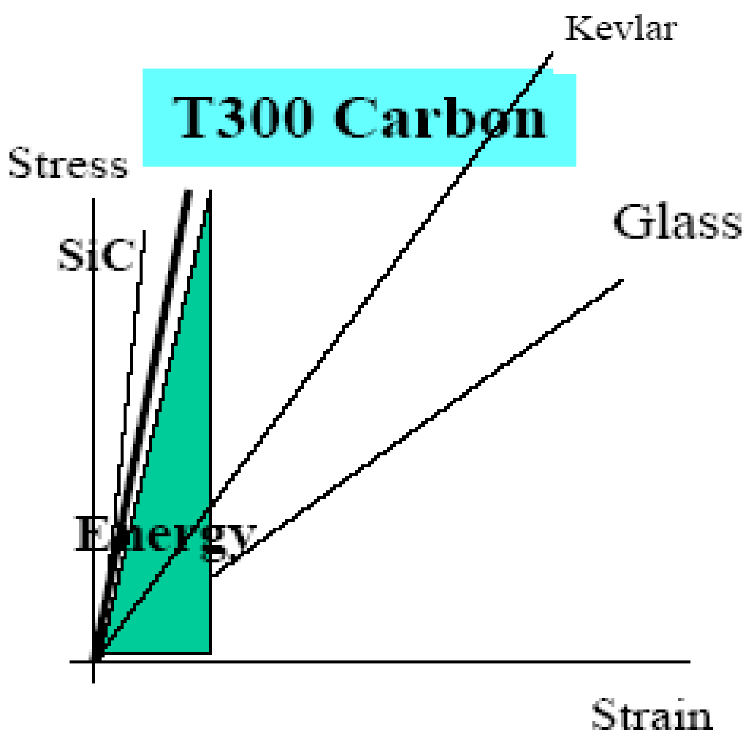


Composites

Polymer Matrix Composites (PMC) – Carbon Fibers

- **Advantages**
  - Simultaneous high stiffness and strength
  - Variety of stiffness and strength grades available
  - Properties do not degrade in the presence of moisture
  - Good strength under sustained load
  - Low thermal expansion
  - Low electromagnetic transmissibility–Electrical Conductivity

- **Disadvantages**
  - Higher cost
  - Less energy absorbed at failure
  - Reactivity with metals



LITERATURE SURVEY

Composites – Fatigue Characteristics

Polymer Matrix Composites (PMC) – Fatigue Observations

- **Why Fatigue Failure is one of the most important failure types of PMCs during their service?**
  - Composites are heterogeneous and anisotropy.
  - Unlike metals, Composite failure types includes,
    - Matrix Cracking
    - Interfacial Debonding
    - Delamination
    - Fiber rupture

PMC – Fatigue Observations – "*An improved Puck's failure theory for fiber-reinforced composite laminates including the in situ strength effect*" by H Dong et al., 2016

Both criteria consider failure due to longitudinal loads and matrix failure mode due to transverse and shear loads separately.

$$f_f = \left|\frac{\sigma_1}{X}\right| \qquad f_m = \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2$$

$\sigma_1 \geq 0 \Rightarrow X = X_t$

$\sigma_1 < 0 \Rightarrow X = X_c$

$\sigma_2 \geq 0 \Rightarrow Y = Y_t$

$\sigma_2 < 0 \Rightarrow Y = Y_c$

Modified Puck Criterion :

$$f_m = \frac{\sigma_2^2}{Y_t Y_c} + \frac{\tau_{12}}{S^2} + \left(\frac{1}{Y_t} + \frac{1}{Y_c}\right)\sigma_2$$

Interfiber Failure (IFF) :

$$\sqrt{\left(\frac{\tau_{21}}{R_{\perp\parallel}}\right)^2 + \left(1 - p_{\perp\parallel}^{(+)}\frac{R_\perp^{(+)}}{R_{\perp\parallel}}\right)^2\left(\frac{\sigma_2}{R_\perp^{(+)}}\right)^2} + p_{\perp\parallel}^{(+)}\frac{\sigma_2}{R_{\perp\parallel}} = 1 \text{ for mode A } (\sigma_2 \geq 0)$$

$$\frac{1}{R_{\perp\parallel}}\left(\sqrt{\tau_{12}^2 + \left(p_{\perp\parallel}^{(-)}\sigma_2\right)^2} + p_{\perp\parallel}^{(-)}\sigma_2\right) = 1 \text{ for mode B } \left(\sigma_2 < 0 \text{ and } 0 \leq \left|\frac{\sigma_2}{\tau_{21}}\right| \leq \frac{R_{\perp\perp}^A}{|\tau_{21c}|}\right)$$

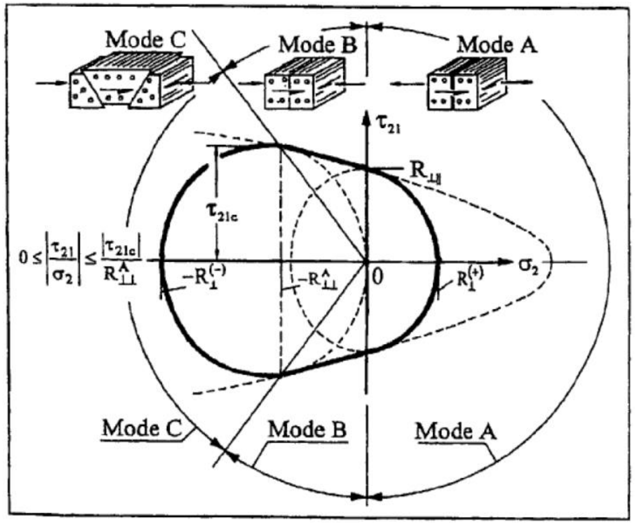
$$\left[\left(\frac{\tau_{21}}{2(1 + p_{\perp\perp}^{(-)})R_{\perp\parallel}}\right)^2 + \left(\frac{\sigma_2}{R_\perp^{(-)}}\right)^2\right]\frac{R_\perp^{(-)}}{(-\sigma_2)} = 1 \text{ for mode C } \left(\sigma_2 < 0 \text{ and } 0 \leq \left|\frac{\tau_{21}}{\sigma_2}\right| \leq \frac{|\tau_{21c}|}{R_{\perp\perp}^A}\right)$$

Plane stress state:

Fracture Curve in σ2, τ21 Space for σ1 = 0

Fiber Failure (FF) :

$$\frac{\sigma_1}{X_t} = 1 \quad for \quad \sigma_1 > 0 \quad or \quad \frac{\sigma_1}{X_c} = 1 \quad for \quad \sigma_1 < 0$$



Different default values for the coefficients are set for carbon and glass fiber plies to:

Carbon: $p_{\perp\parallel}^{(+)} = 0.35 \quad p_{\perp\parallel}^{(-)} = 0.3 \quad p_{\perp\perp}^{(+)} = 0.25 \quad p_{\perp\perp}^{(-)} 0.2$

Glass: $p_{\perp\parallel}^{(+)} = 0.3 \quad p_{\perp\parallel}^{(-)} = 0.25 \quad p_{\perp\perp}^{(+)} = 0.2 \quad p_{\perp\perp}^{(-)} 0.2$

Composites – Fatigue Characteristics – Literature Review

PMC – Fatigue Observations – "*A New Fatigue Theory for Multidirectional Fiber-Reinforced Composite Laminates with Arbitrary Stacking Sequence*" by H Dong et al., 2016

- The author in this paper develops a new fatigue failure theory for multidirectional fiber reinforced composites by combining non-linear residual strength and stiffness models with improved Puck's Failure theory.
- The fatigue failure model consists of,
  - Constitutive relations for the analysis of strains and Stresses in the plies and the laminates.
  - The application of the Failure criterion to determine the ultimate failure of the laminate.
  - Imparting the degradation model during the analysis of strains and the stresses in the plies and the laminates.

- The paper suggests the use of linear classical laminate theory for the analysis of the stresses and the strains in the plies and the laminates.
- The failure criterion consists of in-situ strength effect and has both fiber failure and the inter-fiber failure.
- The degradation model involves residual strength and residual stiffness calculations upon increasing number of cycles. It is given by,

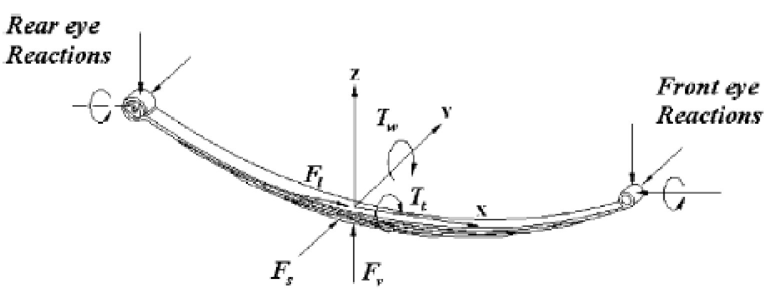
$$\frac{R_n - \sigma_{max}}{R_0 - \sigma_{max}} = 1 - \left(\frac{\log n}{\log N_f}\right)^{\alpha};$$

$$\frac{E_n - \sigma_{max}/\epsilon_f}{E_0 - \sigma_{max}/\epsilon_f} = 1 - \left(\frac{\log n}{\log N_f}\right)^{\beta}$$

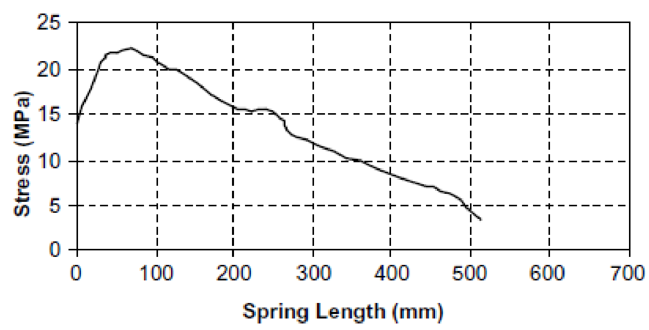
Composite Leaf Springs – Literature Review

Composite Leaf Springs – "*Analysis and optimization of a composite leaf spring*" by Mahmood M. Shokrieh et al., 2003

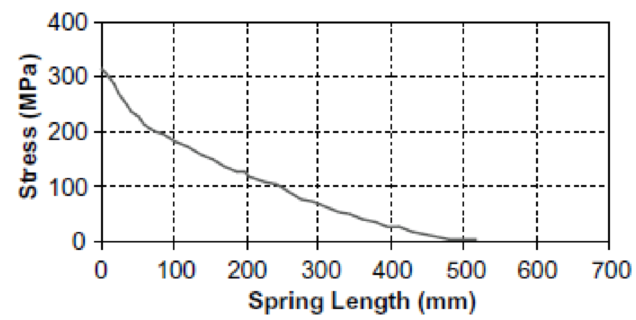
- The objective of this paper was to obtain a spring with minimum weight that is capable of carrying given static external forces without failure. The design constraints were stresses (Tsai–Wu failure criterion) and displacements.
  - Compared to the steel spring, the optimized composite spring has stresses that are much lower, the natural frequency is higher and the spring weight without eye units is nearly 80% lower.
  - The optimum spring width decreases hyperbolically and the thickness increases linearly from spring eye towards the axle seat.
  - The stresses in the composite leaf spring are much lower than that of the steel spring.



Model



Longitudinal Stress

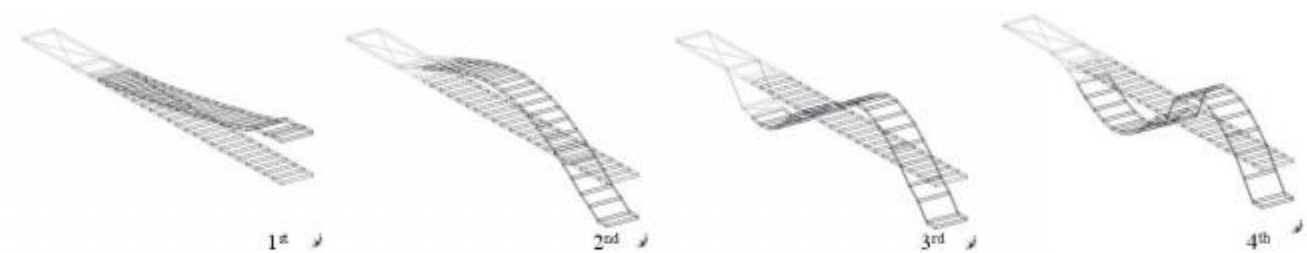


Lateral Stress

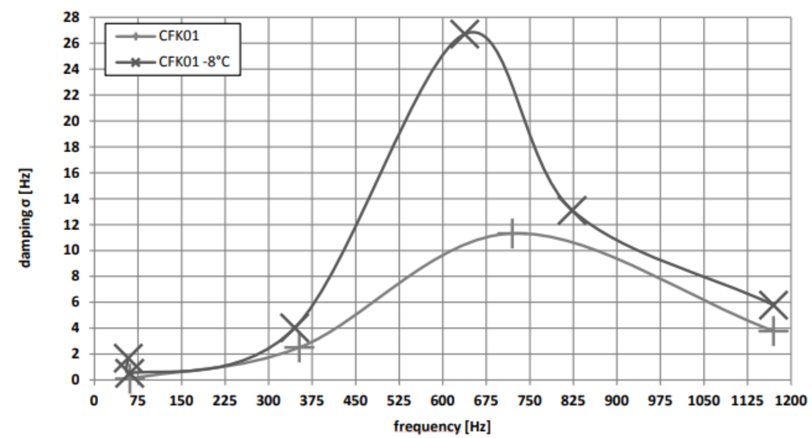
Experimental Modal Analysis – Literature Review

Composite Leaf Springs – "*Investigation of the Dynamic Behaviour of CFRP Leaf Springs* " by Stephan Krall et al., 2014

- The authors in this paper discuss the dynamic behaviour of CFRP leaf springs. Some of the observations in this paper were,
  - A standard steel spring was used as reference.
  - Three different composite springs were investigated and compared.
  - The composite design was calculated via classical lamination theory and the manufacturing was done by hand lay-up and autoclave.



Mode Shapes of CFRP Leaf Spring

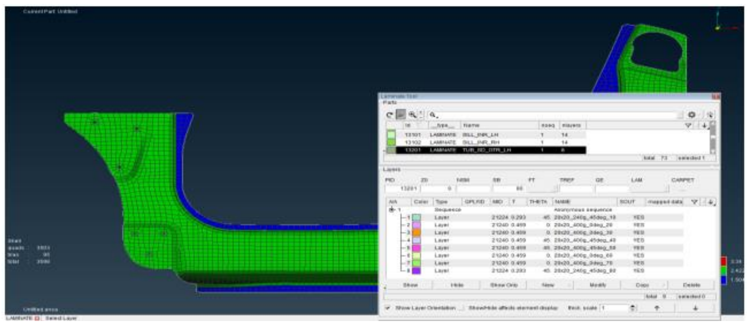


Modal Damping ratio v/s Resonance Frequency of CFRP at 23C and -8C.

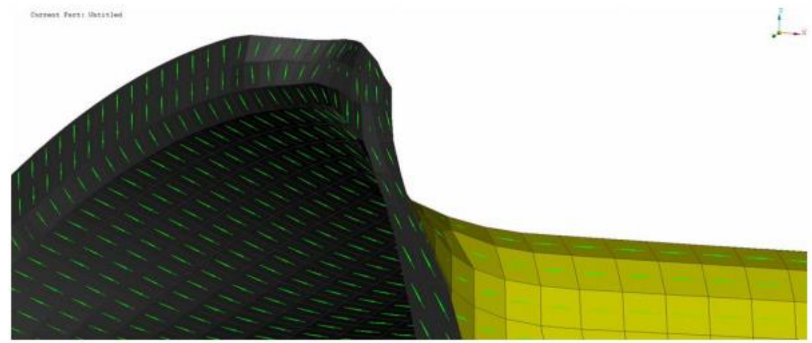
ANSA Finite Element Modeling – Literature Review

Composite Modeling – "*Composite Model Building For Automotive CAE*" by Stuart Davies at 5th BETA CAE

- The authors in this paper discuss the LAMINATE module in ANSA for composite modeling. The brief procedure to use this LAMINATE module are,
  - Surface were discretized with shell elements and oriented accordingly.
  - Ply boundaries were cut into the mesh, including staggered boundaries .
  - Layup defined using ANSA LAMINATE tool.



Laminate tool



Material Orientation

LIFE PREDICTION METHODOLOGY

COMPOSITES – Life Prediction Methodology

Fatigue Life Prediction of Polymer Matrix Composites - Assumptions

- The classical lamination theory is only valid for thin laminates (span a and b > 10×thinckness t) with small displacement w in the transverse direction (w << t)
- Perfect bonding between layers is assumed.
- Each lamina is considered to be a homogeneous layer such that its effective properties are known.
- Each lamina is in a state of plane stress.
- The linear classical laminate theory is used to evaluate the stresses and the strains of the plies and the laminates.
- The additional load could cause the immediate failure of the other laminae and leads to total failure of the laminate. In this case, the first lamina failure is the failure of the laminate
- A theoretical initial life cycle is assumed for a composite material to initiate the fatigue life prediction in order to avoid expensive experimental testing.
- The initial static strength is assumed to be 60% of the overall static strength in order to achieve Reserve factor of 1.67 for the composite materials.
- The fatigue loading cycle is assumed to be arbitrary stress ratio in order to achieve the goal of life prediction methodology independent of the stress ratios.
- The temperature effect is not considered and is assumed to be room temperature conditions.
- The fatigue life prediction methodology is considered for static type loading. Transient loading will be considered at future work.

COMPOSITES – Life Prediction Methodology

Fatigue Life Prediction of Polymer Matrix Composites – Steps Involved

- The Fatigue life prediction for composite laminates involves three major steps. Such as,

1. Use ***Finite Element Method*** with the application of ***Composite Laminate Theory*** to check Stresses and Strains at each lamina level as well as at the laminate level.
2. Application of ***Composite Failure Theory*** during the simulation at every stage to check the state of failure at each lamina level as well as laminate level.
3. Application of ***Predicted Material Degradation*** upon increasing number cycles during the simulation. This helps in predicting the number of cycle to failure of the composite laminate with arbitrary stacking sequence and arbitrary fatigue loading at different stress ratios.

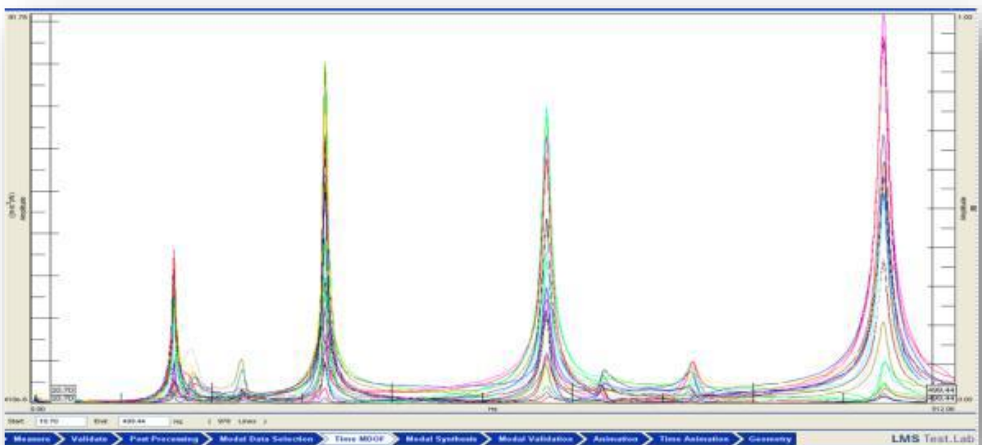
- This comprehensive methodology provides a ***Generic Approach*** to predict the Life of the Composite Laminates.
- The suggested Generic approach is independent of Stacking Sequence, Loading types and Material Orientations.

EXPERIMENTAL MODAL ANALYSIS

Leaf Spring Experimental Modal Analysis

Experimental Modal Analysis (EMA) Observations

- EMA involves mechanically exciting the system under test via impulse, then measuring the resulting vibratory response.
- The first natural frequency was observed to be 25.27 Hz.
- In the Frequency Response Functions plots, we have found no resonance effects at these natural frequencies.



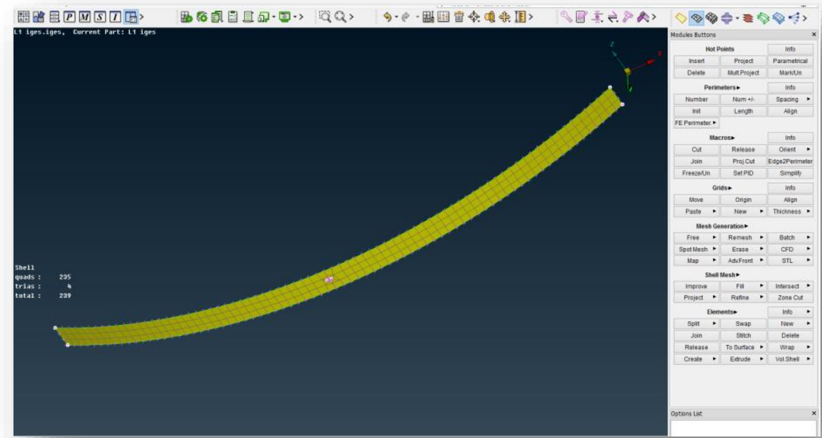
Modes	Experimental Results (Hz)	Numerical Results (Hz)
1	25.27	27.49
2	77.06	70.52
3	112.45	114.48

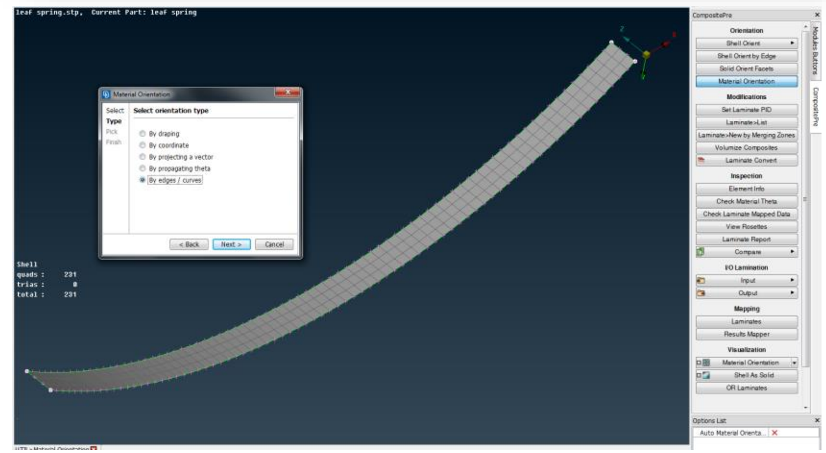
ANSA COMPOSITE MODELING

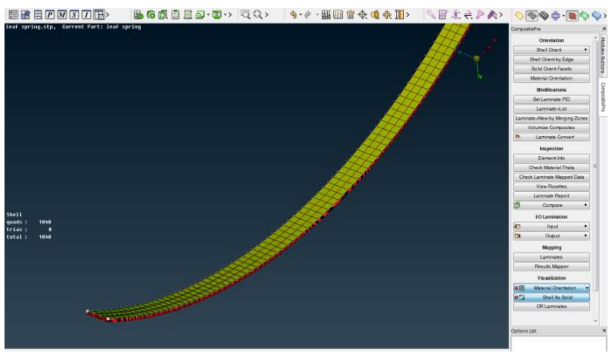
ANSA Composite FE Modeling

Finite Element Modeling – Composite Leaf Spring

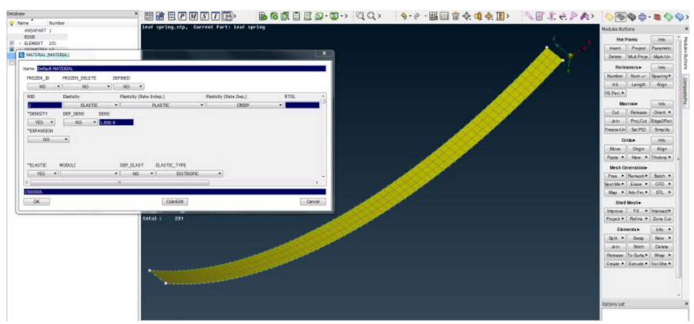
- The suggested methodology is applied over a eight layers CFRP laminate with each having 1mm thickness.
- The Unidirectional Lamina is set at Zero degree orientation and also stacked up to 8mm leaf spring thickness.
- This FE model was then used an input to solve in Ansys Structural Analysis module.
- Two types of Composite Materials were considered.
    - CFRP – Carbon Fiber Reinforced Polymers
    - GFRP – Glass Fiber Reinforced Polymers







8 Layers Shells



Material PID

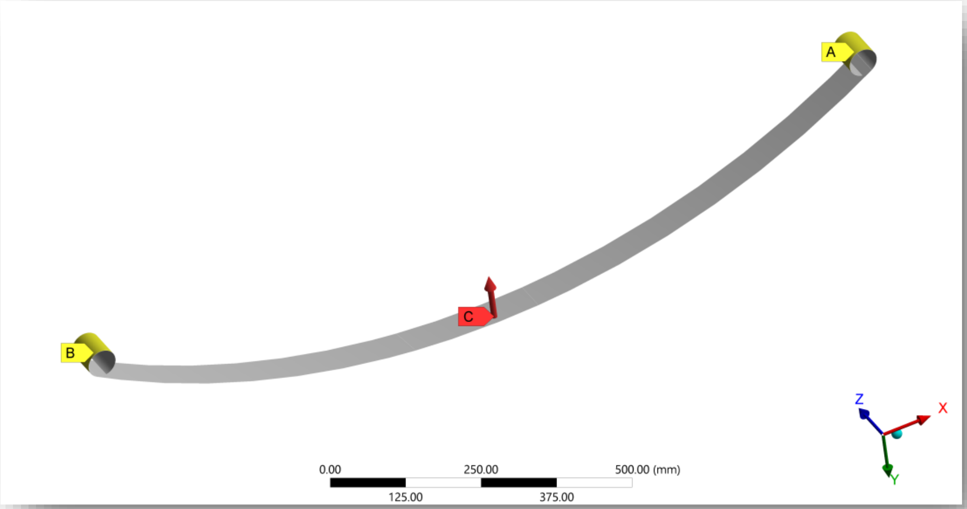
2D Shell (Above); Orientation (Below)

Composite FE Modeling

Finite Element Modeling – Composite Leaf Spring – Boundary Conditions

- The mesh file is provided with the boundary conditions as follows,
    - One eye was fixed.
    - Another eye with axial DOF free.
- The vertical load of 165.2 N (1/3rd of the mass of the suspension and the wheel assembly) was provided at the center.

- This solver deck will now be solved for the entire strength and stiffness degradation parameters.
- Each stress values at corresponding degradation parameter was noted.
- Puck's failure criterion is applied to check the reserve factor for each ply.



COMPOSITE LEAF SPRING LIFE PREDICTION

Composite FE Modeling

Finite Element Modeling – Composite Leaf Spring – Predicted Strength Degradation

- With the help of ***Predicted Material Degradation***, it is possible to predict the number of cycle to failure of the composite laminate with arbitrary stacking sequence and arbitrary fatigue loading at different stress ratios.

Theoretical Strength Degradation Equation

<u>Residual Strength Degradation</u>

$$\log(N_f) = -a\log(\sigma(n)) + b$$

$$\left(\frac{R(n)^{\gamma} - \sigma(n)^{\alpha}}{R(o)^{\gamma} - \sigma(n)^{\alpha}}\right) = 1 - \left(\frac{Log(n)}{Log(N_{f_i})}\right)^{\beta}$$

- N_f = Number of Cycles to Failure
- N_{fi} = Initial assumed life expectancy of the laminate
- n = number of cycles
- σ(n) = Static Strength with respect to number of cycles (MPa)
- R(n) = Residual Strength with respect to number of cycles (MPa)
- R(o) = Initial Residual Strength (MPa)
- a, b = Constants
- γ,α,β = Curve fitting Parameters to be found experimentally

Composite FE Modeling

Finite Element Modeling – Composite Leaf Spring – Predicted Stiffness Degradation

Theoretical Stiffness Degradation Equation

Residual Stiffness Degradation

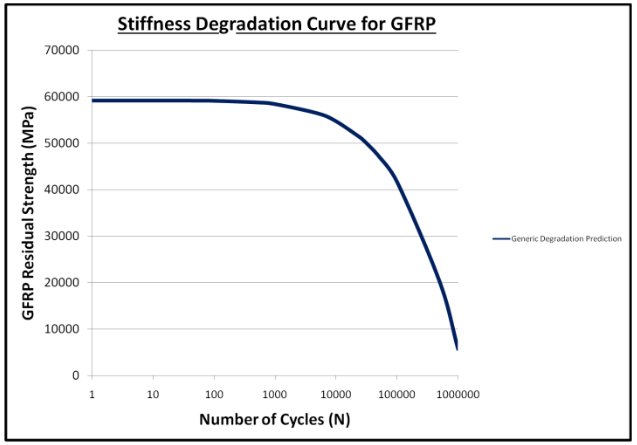
$$\log(N_f) = -a\log(S(n)) + b$$

$$\left(\frac{E(n)^{\gamma} - \left(S(n)/\epsilon_f\right)^{\alpha}}{E(o)^{\gamma} - \left(S(n)/\epsilon_f\right)^{\alpha}}\right) = 1 - \left(\frac{Log(n)}{Log(N_{f_i})}\right)^{\beta}$$

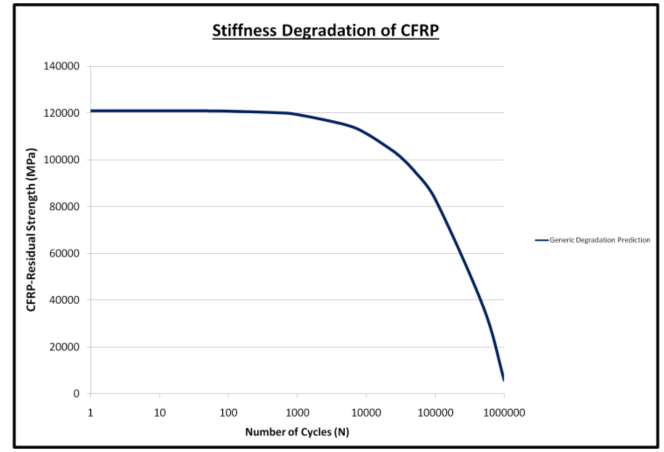
- N_f = Number of Cycles to Failure
- N_{fi} = Initial assumed life expectancy of the laminate
- n = number of cycles
- S(n) = Alternating Stress with respect to number of cycles (MPa)
- ϵ_f = Static Strain
- E(n) = Residual Stiffness with respect to number of cycles (MPa)
- E(o) = Initial Residual Stiffness (MPa)
- a, b = Constants
- γ,α,β = Curve fitting Parameters to be found experimentally

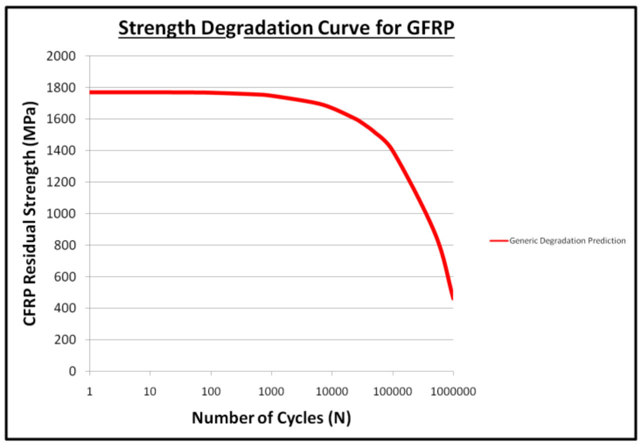
Composite FE Modeling – Residual Property Inputs

Composite Leaf Spring – Predicted Strength and Stiffness Degradation Results – GFRP and CFRP

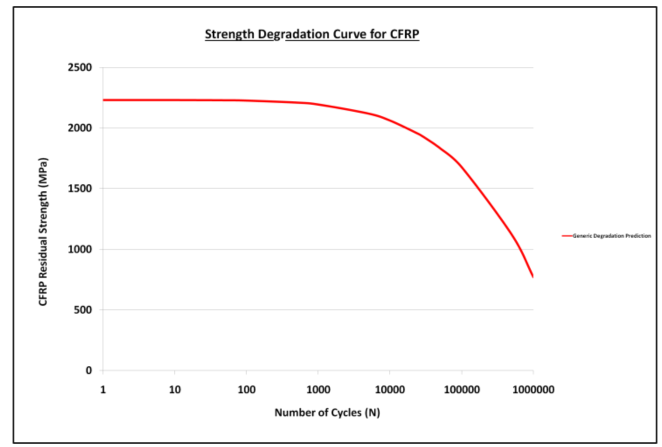


$$\left(\frac{E(n)^{\gamma} - \left(S(n)/\epsilon_f\right)^{\alpha}}{E(o)^{\gamma} - \left(S(n)/\epsilon_f\right)^{\alpha}}\right) = 1 - \left(\frac{Log(n)}{Log(N_{f_i})}\right)^{\beta}$$



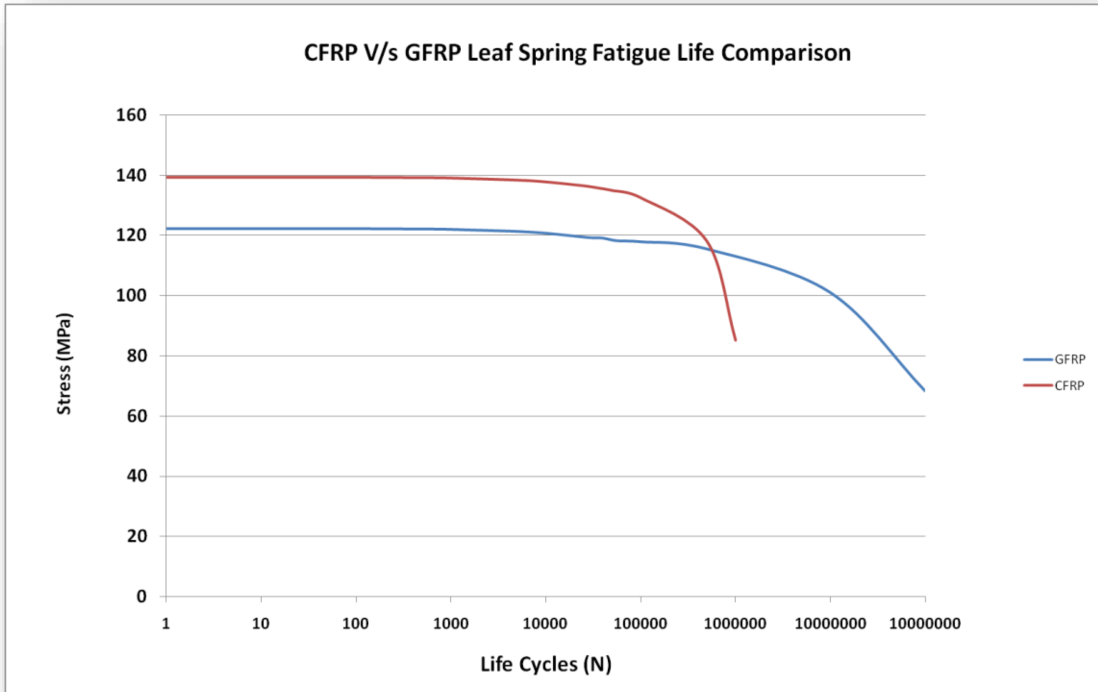


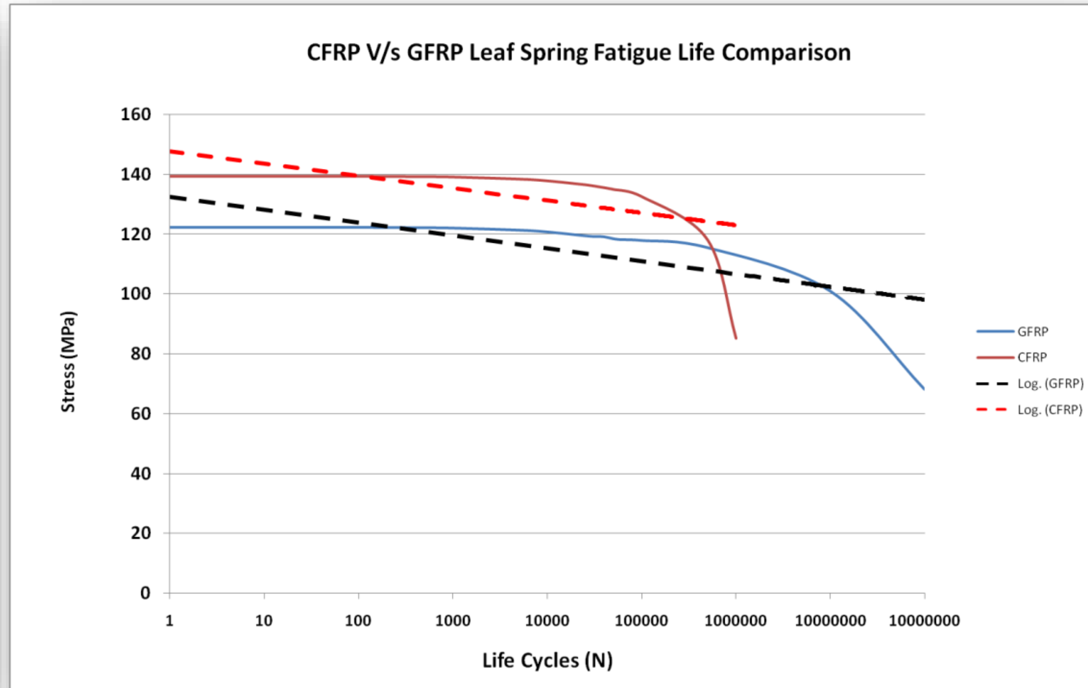
$$\left(\frac{R(n)^{\gamma} - \sigma(n)^{\alpha}}{R(o)^{\gamma} - \sigma(n)^{\alpha}}\right) = 1 - \left(\frac{Log(n)}{Log(N_{f_i})}\right)^{\beta}$$



Composite FE Modeling - Results

Composite Leaf Spring – Predicted Life Curve for CFRP and GFRP Leaf Springs





CONCLUSION

Composite Life Prediction of Leaf Spring

Fatigue Life Prediction of Composite Leaf Spring – Conclusion

- The Generic Method actually quantifies the reference theoretical method and predicts the life expectancy of the composite leaf spring to be more than 1E7 cycles for GFRP Leaf Spring and around 5E6 cycles for CFRP Leaf Spring.
- Since, the laminate consists of Unidirectional (UD) laminae, the last ply which undergoes tension was more prone to fail first due to the presence of tensile/compressive loading in contrast with the angle and cross plies.
- Ply-by-Ply basic fatigue life analysis using Classical Lamination theory with the help of robust Finite Element Method effectively considers the failures at each lamina level.
- The reserve factor which is inverse of safety factor can be obtained for each ply. It was assumed that, any ply which has Inverse reserve factor (IRF) more than 1 will be considered as failure.
- Thus, the first ply which had undergone >1 IRF was the 8^{th} ply for the GFRP leaf spring and 6^{th} ply for the CFRP leaf spring at its corresponding life cycle values.
- Based on the first ply failure theory, it can be considered that the entire GFRP leaf spring has failed beyond 1E7 cycles and CFRP leaf spring has failed beyond 5E6 cycles.

>Note<

- ANSA laminate tool was able to build this model within **30 mins**, compared to 90-270 mins on other competitive software's.
- By using this model, the number of experiments to characterize the material properties of a Composite Lamina can be minimized.
- Since, the technique involves progressive damage modeling, it is possible to conduct fatigue analysis at the component level analyzing complex loading conditions.

CALL TO ACTION – FUTURE WORK

Composite Life Prediction of Leaf Spring

Fatigue Life Prediction of Composite Leaf Spring – Future Scope

- It is important to note that Composites are heterogeneous and anisotropy. Thus, universal application of any theory requires thorough experimental validations and this technique also requires experimental validation.
- The technique shall be used for different loading conditions like dynamic loadings.
- There is scope of composite optimization in predicting the optimum layers, thickness and orientations which can give best life expectancies for different applications.
- The effect of temperature, humidity and other environmental conditions needs to be evaluated since composites are sensitive to environmental conditions.
- The residual properties at different directions and its distributions with respect to the number of cycles needs to be evaluated.

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THANK YOU..!